Convective Influence on the Lower Stratospheric Water Vapor in the Boreal Summer Monsoon Region

Rei Ueyama[1]*, Eric Jensen[1], Leonhard Pfister[1], and Mark Schoeberl[2]

* rei.ueyama@nasa.gov

[1]NASA Ames Research Center, Moffett Field, CA; [2]Science and Technology Corporation, Columbia, MD

Introduction

The Tropical Tropopause Layer (TTL), a transition layer between the upper troposphere and the lower stratosphere in the tropics, serves as the entryway of various trace gases into the stratosphere. Of particular importance is the transport of water vapor (H_2O) through the TTL. Stratospheric H_2O not only impacts climate through its greenhouse forcing, but it also plays a significant role in stratospheric chemistry by affecting polar stratospheric cloud formation and the ozone budget. Stratospheric humidity is mainly controlled by the freeze-drying of tropospheric air as it ascends across the tropical cold-point tropopause (Fig. 1a). The details of the TTL dehydration mechanism, including the roles of deep convection, gravity waves, and cloud microphysical processes (Fig. 1b), are not well understood, particularly during the boreal summer when temperature plays a less direct role on the lower stratospheric humidity than in boreal winter.

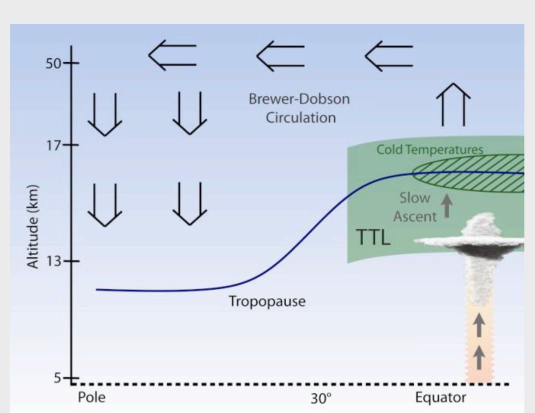
The atmospheric general circulation in the boreal summer is dominated by the Asian and North American monsoons, which are essentially sea breeze circulations on continental and seasonal scales driven by diabatic heating associated with convection. These monsoon circulations serve as a conduit for trace constituent transport, including H_2O, from the boundary layer into the lower stratosphere.

The goal of this research is to better understand the processes that control H_2O and cirrus clouds in the TTL over the boreal summer monsoon regions.

★ How well do our trajectory and cloud microphysical models simulate the observed H_2O and clouds in the TTL during boreal summer?

★ What is the impact of convection on TTL humidity and cirrus cloud occurrence over the boreal summer monsoon regions?

★ How important is the direct injection of H_2O and anvil ice by overshooting deep convection on TTL humidity and clouds?

(a) 

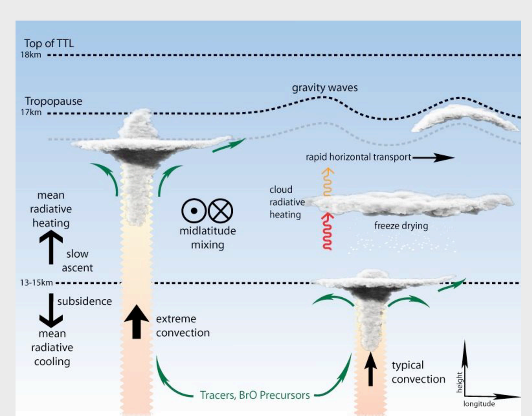
(b) 

Fig. 1: (a) Schematic of the zonal mean cross-section of the TTL where air is dehydrated ("freeze-dried") as it ascends through the cold-point tropopause. (b) Longitude-height cross-section of the TTL and the many processes that influence TTL humidity and clouds.

Conclusions

1. Trajectory and cloud microphysical model simulations of the 100 hPa level water vapor (H_2O) mixing ratios and cloud occurrence frequencies in the TTL (15-17 km) are in reasonable agreement with MLS and CALIPSO satellite observations, respectively, allowing for an investigation of the convective impact on lower stratospheric humidity.
   - Averaged over the tropics, convection moistens the 100 hPa level by ~0.5 ppmv and increases the cloud occurrence frequency in the TTL by ~7%.
   - Convective impact on TTL humidity and clouds is primarily due to the saturating effect of convection; convectively-detrained ice has negligible impact.
2. Convection contributes significantly to the observed H_2O enhancement over the Asian monsoon region.
   - Convection moistens the Asian monsoon region by ~1 ppmv at the 100 hPa level, where ~80% of this moistening is due to convection occurring locally within the Asian monsoon region. Contribution by very deep convective cloud systems (cloud tops >375 K, <105 hPa) is significant (~40%).
   - Convection increases cloud occurrence frequencies in the TTL over the Asian monsoon region by ~26%, where ~65% of this increase is due to convection occurring locally within the Asian monsoon region.
3. Contrary to MLS observation, H_2O enhancement over the North American monsoon region is virtually absent in the model, which may be associated with uncertainties in the convective cloud top heights in this region.

Methodology

Trajectory Model

1. Calculate 60-day backward (diabatic) trajectories from 3 Aug 2007 at
   - every 2° latitude x 2° longitude grid points in the 10°S - 50°N domain
   - 379 K potential temperature (~100 hPa) level

Data sources
- Boreal summer (Jun – Aug 2007) mean, offline calculations of tropical radiative heating rates [*Yang et al.*, 2010] merged with ERA-Interim extratropical heating rates (Fig. 2)
- ERA-Interim temperatures and winds with enhanced wave-driven variability [*Kim and Alexander,* 2014] (Fig. 3)
- Parameterization of waves with periods less than two cycles per day that are not resolved in the 6-hourly analysis fields [*Jensen and Pfister, 2004*]

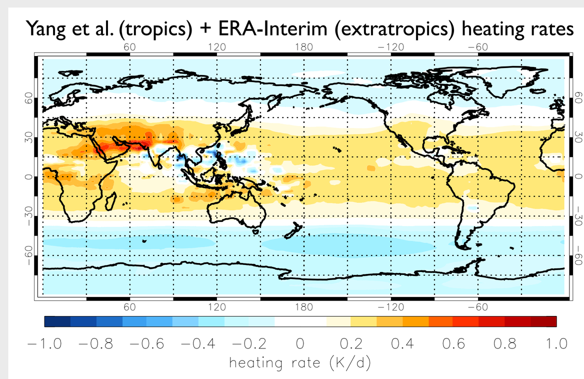


Fig. 2: Boreal summer (JJA 2007) radiative heating rates at the ~100 hPa level based on Yang et al. data (tropics) merged with ERA-Interim (extratropics) data.

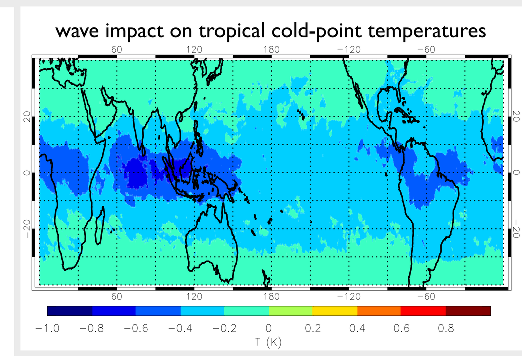


Fig. 3: Tropical cold-point temperature difference due to subgrid-scale waves [*Kim and Alexander,* 2014] in boreal summer (JJA 2007). Waves lower the cold-point temperature throughout the tropics by ~0.3 K.

Cloud Microphysical Model

✦ **Time-dependent, one-dimensional (vertical) model that tracks the growth, sedimentation, sublimation of ice crystals**

2. Simulate clouds along parcel trajectories and calculate their effects on H_2O mixing ratios in the TTL
   - Initialize the model with MLS H_2O profiles at Day 0 (earliest day of the trajectories)
   - Apply the MLS averaging kernel on the simulated H_2O profiles at Day 60

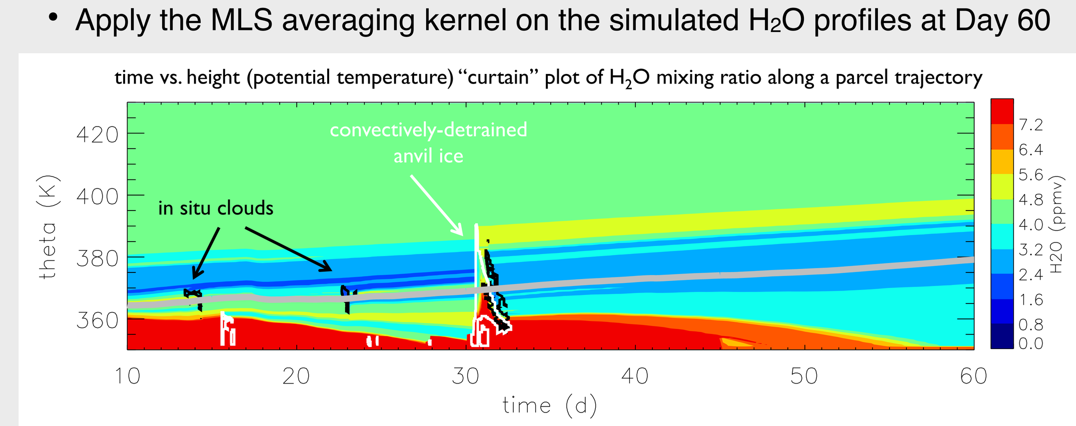


Fig. 4: A sample time-height "curtain" of H_2O mixing ratio of a given parcel trajectory. Day 60 is the start of the backward trajectory (i.e., latest time). This parcel's altitude is shown in gray line.

‣ TTL humidity is influenced by *in situ formed clouds* (black contours) which generally dehydrate, and *convection* which hydrate (saturate) up to the cloud top altitude (e.g., high H_2O mixing ratios below ~360K). *Convectively-detrained anvil ice* (white contours) may occasionally dehydrate (e.g., Day 31).

✦ **Convection scheme**
- Trace the trajectories through 3-hrly convective cloud-top height fields, which are based on TRMM/GPM rainfall data and geostationary infrared satellite cloud-top measurements; cloud-top altitudes are adjusted to match the CloudSat, CALIPSO, and CATS measurements.

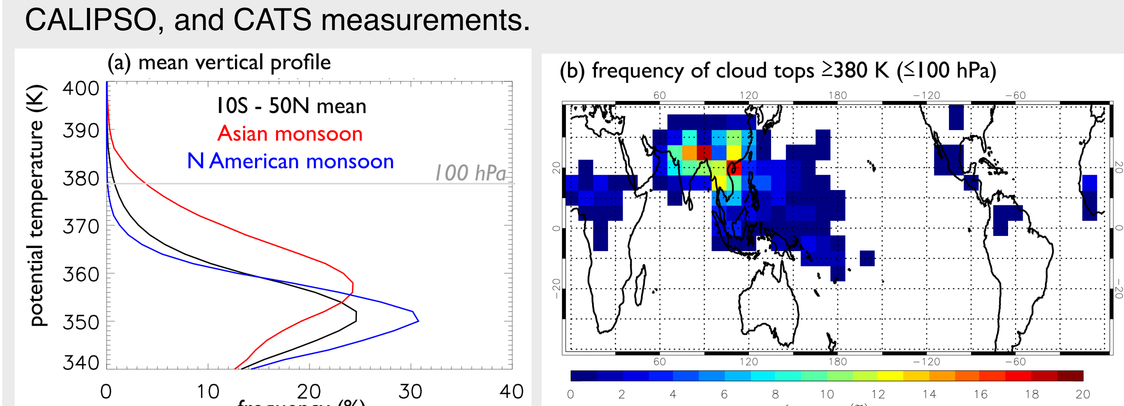


Fig. 5: Convective cloud-top height distribution in the boreal summer (JJA 2007): (a) vertical profile, (b) spatial distribution of convective clouds with tops ≥380 K levels.

Observations

3. Compare simulated data with observations:
   - MLS H_2O at 100 hPa level
   - cloud occurrence frequencies calculated from CALIPSO cloud profiles

Results

Model *vs.* Observations

- The 100 hPa H_2O field and TTL cloud occurrence frequencies in the model agree reasonably well with MLS and CALIPSO observations, respectively.
- Model biases include the lack of H_2O enhancement over the N American monsoon region and the overestimation of cloud occurrence in the eastern sector of the Asian monsoon region and eastern-central tropical Pacific.

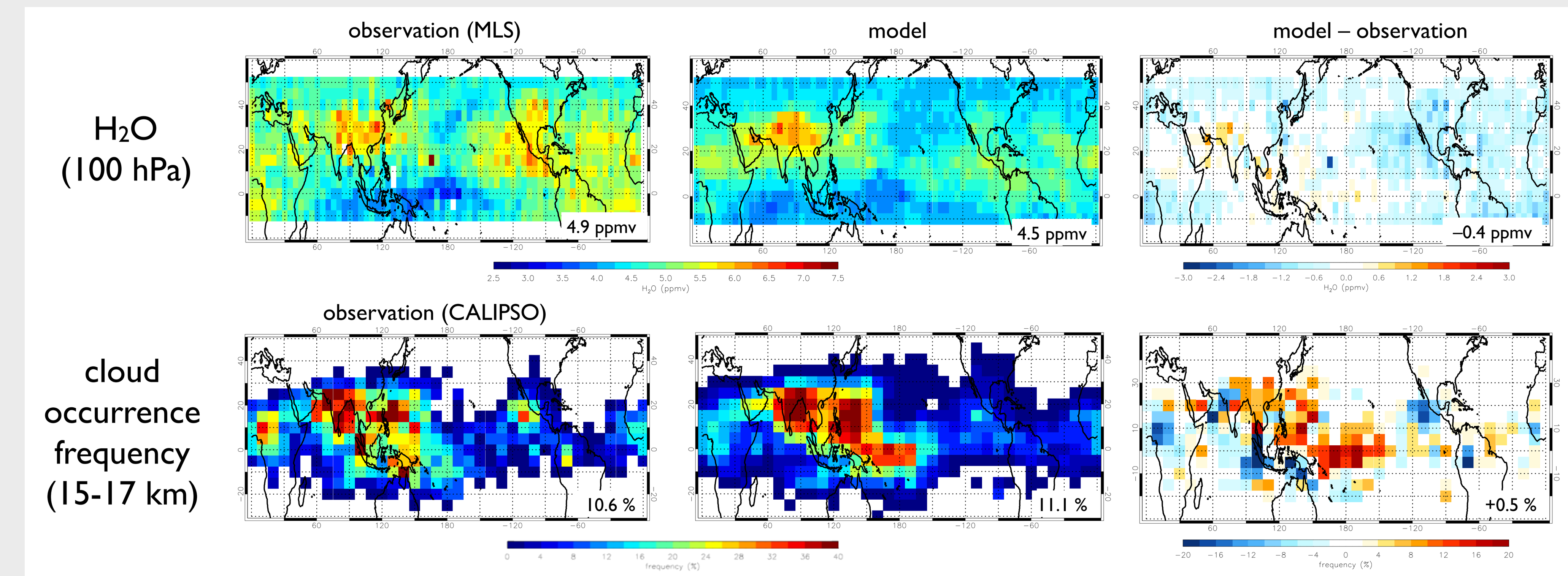


Fig. 6: (top) The 100 hPa H_2O mixing ratios on (7-day mean centered on) 3 Aug 2007: (left) MLS observation, (middle) model with MLS averaging kernel applied, (right) difference. (bottom) Cloud occurrence frequencies in the TTL (15-17 km) during 4 Jul – 3 Aug 2007: (left) CALIPSO observation, (middle) model, (right) difference. Domain average values are indicated in the bottom right corner of each panel.

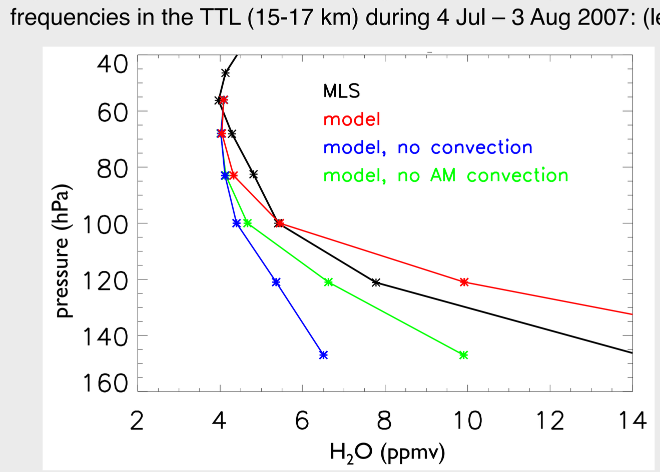


Fig. 7: Vertical profiles of H_2O mixing ratio averaged over the Asian monsoon region (15°S-35°N, 45-120°E): (black) MLS, (red) model with convection, (blue) model without convection, (green) model without Asian monsoon convection (0-40°N, 40-140°E).

‣ The H_2O enhancement over the Asian monsoon region at the 100 hPa level, as observed by MLS, is well simulated in the model (Figs. 6, 7).
- Convection, particularly those in the Asian monsoon region, contribute significantly to the moistening of the TTL below the 83 hPa level (Fig. 7).

‣ Cloud occurrence frequencies in the model agree well with those of CALIPSO over the Asian monsoon region at and above the cold point ~16.5 km (Fig. 8).
- Convection increases cloud occurrence throughout the TTL, but primarily in the lower TTL with ~50% contribution from convection occurring locally within the Asian monsoon region.

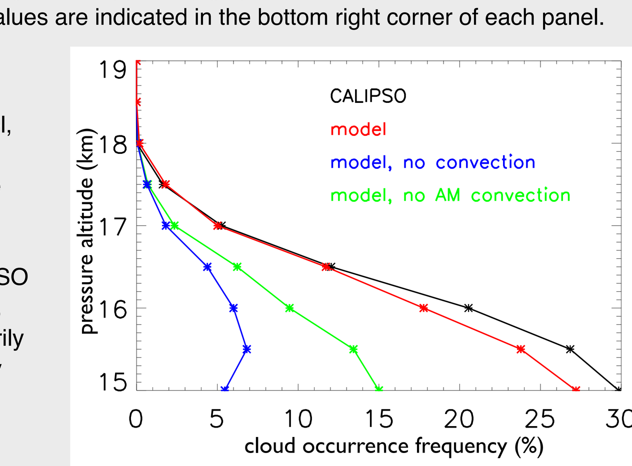


Fig. 8: Vertical profiles of cloud occurrence frequency during 4 Jul – 3 Aug 2007 averaged over the Asian monsoon region: (black) CALIPSO, (red) model with convection, (blue) model without convection, (green) model without Asian monsoon convection.

Sensitivity Tests

- Averaged over the tropics, convection moistens the 100 hPa level by ~0.5 ppmv and increases the TTL cloud occurrence frequency by ~7%.
- Convection moistens the Asian monsoon region (+1 ppmv at the 100 hPa level) and increases the TTL cloud occurrence frequency (+26%) over the region.
- Convection occurring locally within the Asian monsoon region explains about 80% of the total convective moistening and 65% of the total cloud increase.

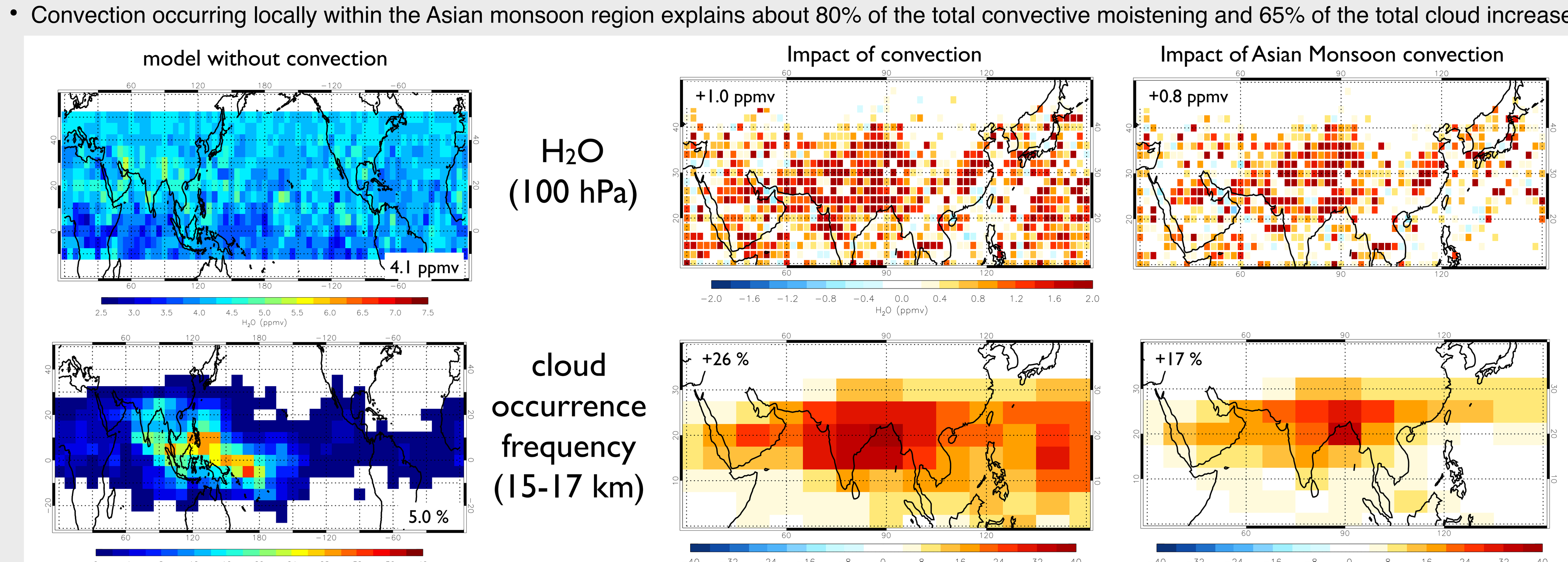


Fig. 9: (left) The 100 hPa H_2O mixing ratios and TTL cloud occurrence frequencies (as in Fig. 6, middle column) in the simulation without convection. The impacts of (middle) global convection and (right) Asian monsoon convection (0-40°N, 40-140°E) on the 100 hPa H_2O and TTL cloud occurrence frequency over the Asian monsoon region.

Impact of deep convection

- Most of the H_2O enhancement over the Asian monsoon region is contributed by convection well above the 365K level, with very deep convective convective systems (convective cloud top potential temperature >375K) accounting for ~40%.
- Convectively-detrained ice has negligible impact on TTL humidity and cloud occurrence (not shown).

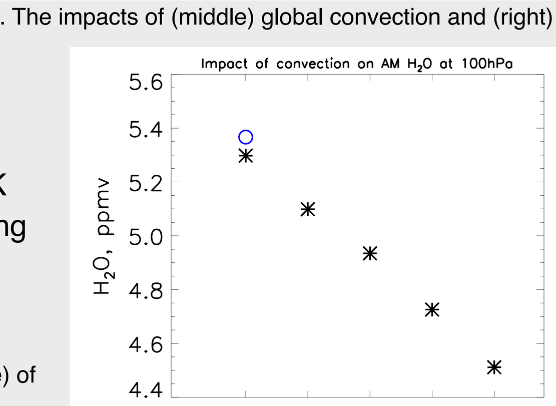


Fig. 10: The average simulated 100 hPa H_2O mixing ratios over the Asian monsoon region plotted versus the maximum height (potential temperature) of deep convection included in the simulations. The MLS-observed H_2O mixing ratio is plotted in blue.